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Sediment Transport in the Colorado River Basin

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ABSTRACT: The Colorado River basin in the southwestern United States is one of the most extensively regulated drainages in the world. Total storage provided by two large reservoirs, each with a usable capacity greater than 30 billion m^3 and numerous smaller reservoirs, is approximately four times the mean annual runoff of approximately 17 billion m^3/year. The relatively large reservoir storage capacity is required because of significant variations in annual runoff, a semiarid climate that necessitates irrigation to raise crops, and a need to meet the legal division of water among basin states.

Several of the longest daily sediment-transport records for North American rivers have been collected at gaging stations in the Colorado River basin. Many of these records of sediment transport are nearly 40 years in length. In 1990, daily samples of sediment transport were collected at only two gaging stations in the basin with more than 10 years of record. Water discharge has been recorded continuously at most of these gages for 60 or more years. Large reservoirs were constructed on each of the three major headwater tributaries during the early 1960s. Daily sediment transport and water discharge records collected at gaging stations in the Colorado River basin over the past 60 years demonstrate that an appreciable change in the hydrology of the Colorado plateau occurred about 1941, and they describe the pre- and postdevelopment hydrologic conditions. These data provide a unique opportunity to investigate the effects of climatic change and the operation of reservoirs on sedimentation and river channel stability.

Water and sediment are not contributed to the channel network uniformly across the Colorado River basin. Furthermore, the principal source areas of water and sediment differ greatly. A majority of the annual water discharge from the basin is supplied by the headwater areas. During the period 1941-57, eighty-five percent of the mean annual discharge is contributed by only 40% of the drainage area. Conversely, tributaries draining semiarid parts of the Colorado plateau, located in the center of the basin, supply 69% of the sediment load, although they constitute only 37% of the drainage area.

Because of the nonuniform supply of runoff and sediment within the Colorado River basin, the location of a reservoir profoundly affects its resulting downstream hydraulic impacts. The hydraulic and morphologic characteristics of river channels adjust over a period of years in order to achieve an equilibrium between the supply and transport of sediment with the available water discharge. Any substantial change in either the sediment load or the water discharge over a period of years will cause a corresponding adjustment in the river channel. The effect of a large reservoir upon the downstream river is complex because both the occurrence (duration) of particular discharges and the sediment load are altered.

INTRODUCTION

The Colorado River is one of the most highly regulated rivers in the world. Total usable reservoir storage capacity exceeds 70 billion m^3, or approximately four times the mean annual flow. The six largest reservoirs in the Colorado River basin, each with a usable storage capacity of 1 billion m^3 or more are shown in Figure 4-1 and listed in Table 4-1. The relatively large reservoir storage capacity is required due to significant variations in annual runoff, a semi-arid climate which necessitates irrigation to raise crops, and a need to meet the legal division of water among basin states. With the exception of relatively small tributaries, flow and sediment transport in the channels of the Colorado River basin have been extensively altered by the construction and operation of reservoirs. Therefore, it is important to understand how these reservoirs have changed the natural flow regime and the quasi-equilibrium adjustment of the channel characteristics to the quantity of sediment supplied to the channels.

The planning and design of the many reservoirs in the Colorado River basin required relatively precise knowledge of annual sediment load throughout the basin. Beginning in 1925, the suspended sediment concentration was sampled daily at two gaging stations in the Colorado River basin: the Colorado River near Grand Canyon, Arizona, and the Colorado River near Topock, Arizona. Over the subsequent 5 years, the sediment-sampling network was expanded to four additional gaging stations located on the

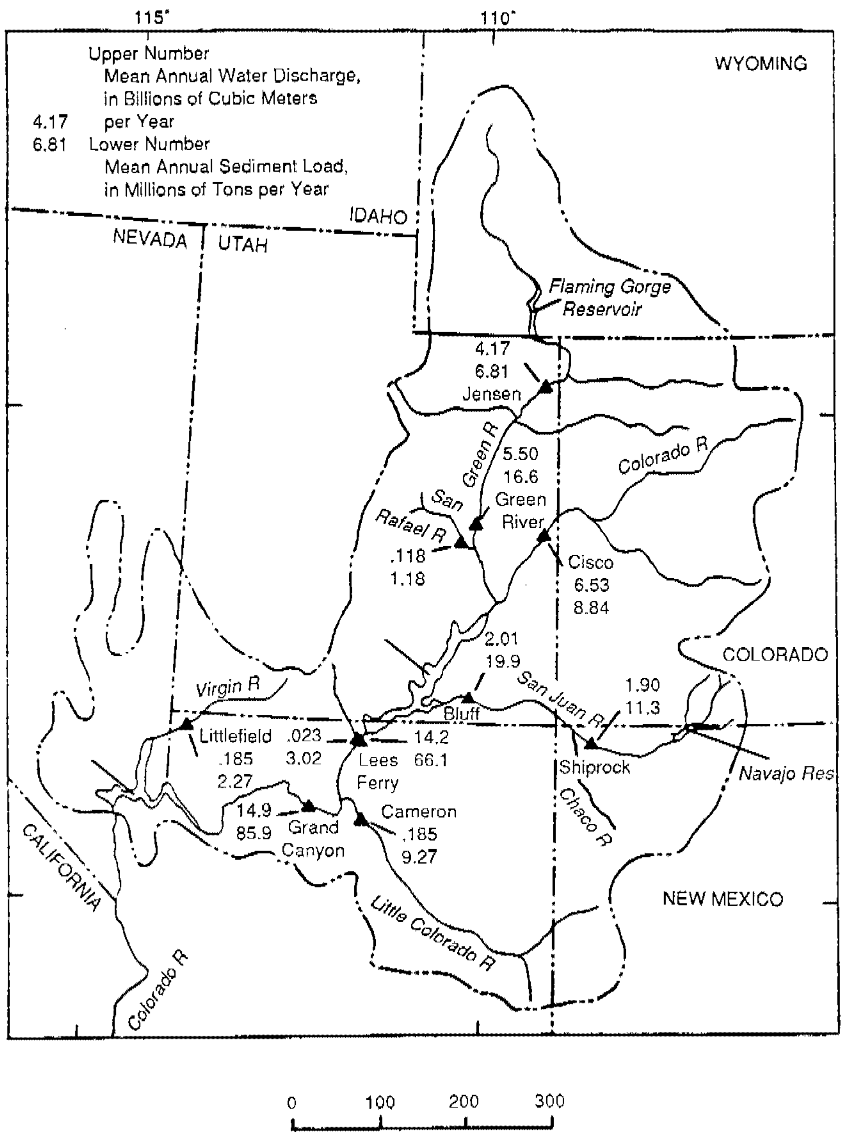

FIGURE 4-1 Mean annual runoff and sediment load at selected gaging stations in the Colorado River basin, 1941-1957.

TABLE 4-1 Reservoirs in the Colorado River Basin upstream from Boulder Dam with more than 0.5 billion m^3 of usable storage capacity.

Reservoir	Usable Storage Capacity (m^3)
Flaming Gorge Reservoir	4.3
Strawberry Reservoir	1.4
Blue Mesa	1.0
Navajo Reservoir	2.1
Lake Powell	31.0
Lake Mead	32.0
TOTAL	71.8

mainstem Colorado River and its major tributaries. By 1957, during the peak of reservoir construction, the suspended sediment concentration was being sampled daily at 18 gaging stations, each of which eventually had a record length exceeding 10 or more years. This network is the most extensive and detailed description of sediment transport in a large drainage basin ever collected. A majority of the reservoirs on the Colorado River and its tributaries were completed by 1963, and the perceived need for an extensive network of long-term sediment-sampling sites was greatly diminished. Sediment sampling was discontinued at one gaging station after another until by the mid-1980s sediment concentration was being sampled at only two of the gaging stations that had more than 10 years of record. Unfortunately, measurements of sediment transport at these gaging stations are not well correlated or indicative of conditions on the Colorado Plateau, which is the principal source area of sediment in the Colorado River Basin.

Over the past three decades, public recognition of the recreational, esthetic, and ecological values present in the streams of the Colorado River basin has grown immensely. Recreational boating through the canyons of the Colorado plateau is extremely popular. Most of these canyons are now included in national parks and national monuments. The Colorado River and its tributaries provide habitat for 11 endangered species of fish. Increased public awareness of the aquatic and riparian resources of the Colorado River basin has coincided with significant alteration on the river as a result of the regulation of flow by and deposition of sediment in reservoirs. Throughout the Colorado River basin, we must determine whether the basin's water resources are being managed wisely and in accordance with the numerous, sometimes conflicting, public benefits.

This chapter reviews our current understanding of sediment transport in the Colorado River basin. The primary objective is to identify and describe the spatial and temporal differences in sediment transport within the basin, which bears significantly upon the future management of the aquatic and riparian resource of the Colorado River basin.

HISTORICAL SAMPLING OF SEDIMENT CONCENTRATIONS

The first systemic samples of suspended sediment in the Colorado River were collected by C. B. Collingwood (1893) at Yuma, Arizona. Over a 7-month period from August 1892 to January 1893, a 1-pint sample was collected daily from the river surface. Samples were evaporated and the dry sediment combined into a monthly total from which an estimate of the sediment concentration was calculated. Beginning in 1900, suspended sediment samples were collected again in the vicinity of Yuma, Arizona, for various periods of time until 1909, when a continuous sampling effort was undertaken by the U.S. Bureau of Reclamation. The first samples of suspended sediment at gaging stations located within the Colorado River basin upstream from Yuma, Arizona, were collected by the U.S. Geological Survey beginning in 1904. Stabler (1911) summarized the measurements at 10 gaging stations in the Colorado River basin. Suspended-sediment concentrations were determined from surface samples collected at a single point in the river cross section during periods when the discharge was relatively constant daily.

These early efforts to describe the characteristics of suspended sediment transported in the Colorado River are difficult to evaluate. The concentration of suspended sediment varies substantially within a river cross section, being greatest near the stream bed below the high velocity and decreasing toward the water surface and the stream banks. Furthermore, the spatial variation in concentration increases with sediment particle size. Even at relatively large discharge when turbulent mixing is greatest, only the silt- and clay-size particles less than 0.062 mm in diameter will be distributed more or less uniformly within a river cross section. Thus, the suspended sediment concentrations reported by the studies cited above are surely less than the actual concentrations. Although the methods were rudimentary and relatively few samples were collected, some of the fundamental characteristics of sediment transport processes in the Colorado River basin were deduced by these early investigations. La Rue (1916) concluded that the largest monthly sediment loads were transported during the peak of the spring snowmelt which had large water discharge but moderate sediment concentration, whereas the largest concentrations of suspended sediment in the lower reach of the Colorado River typically occurred during September and October. La Rue also concluded that a portion of the basin, specifically southeastern Utah and northeastern Arizona, contributed a disproportionately large share of Colorado River sediment.

Because of the need for more precise estimates of annual sediment load in planning reservoirs and the realization that sampling suspended sediment concentration at the river surface was inadequate, the U.S. Geological Survey developed a device and method for collecting a sample from the entire river cross section (Howard, 1930). The device was called the Colorado River sampler. It consisted of a 1-pint bottle held upright in a metal frame above a large sounding weight. The sampler was lowered to the riverbed, where a paper cap on the bottle was punctured by a messenger weight released from the surface; then the sampler was raised. Typically, several vertical segments of the river cross section were sampled and composited to determine the suspended sediment concentration at a given time. A program of sampling cross-sectionally averaged suspended sediment concentrations in the Colorado River at regular intervals began in August 1925 at the Grand Canyon and Topock gaging stations. Over the next five years, the sediment sampling network was expanded to four additional gaging stations: the Colorado River at Cisco, Utah, the Green River at Green River, Utah, the San Juan River at Bluff, Utah, and the Colorado River at Lee's Ferry, Arizona. The first 16 years of the Colorado River Sediment Project were described by Howard (1947).

In April 1944, a substantially improved suspended sediment sampler was adopted. The new sampler was designed so that water flowed into the collection bottle at the same velocity as the local streamflow without the presence of the sampler. During development, the new sampler was tested over a wide range of flow velocities and sediment concentrations and was found to collect a true discharge weighted sample of suspended sediment. With various modifications, this same sampler design is used worldwide today. A comprehensive study of the characteristics of the Colorado River sampler was never conducted. Various laboratory and field comparisons, including these conducted at the San Juan River at Bluff and the Colorado River near Grand Canyon, suggest that the Colorado River sampler would undersample the true concentration by a few to several percent.

The number of daily sediment sampling sites operated during each year from 1925 to 1990 in the Colorado River basin upstream from Lake Mead is shown in Figure 4-2. During the period from 1946 to 1956, the number of gaging stations where suspended sediment was sampled intensively expanded greatly. By 1957, suspended sediment concentration was determined daily at 18 gaging stations in the Colorado River basin where the record length eventually reached 10 years or more. The primary objective of this sampling network was to provide information for the planning and design of reservoirs in the Colorado River basin. Most of these reservoirs were completed by 1963, and the then recognized need for an extensive network of

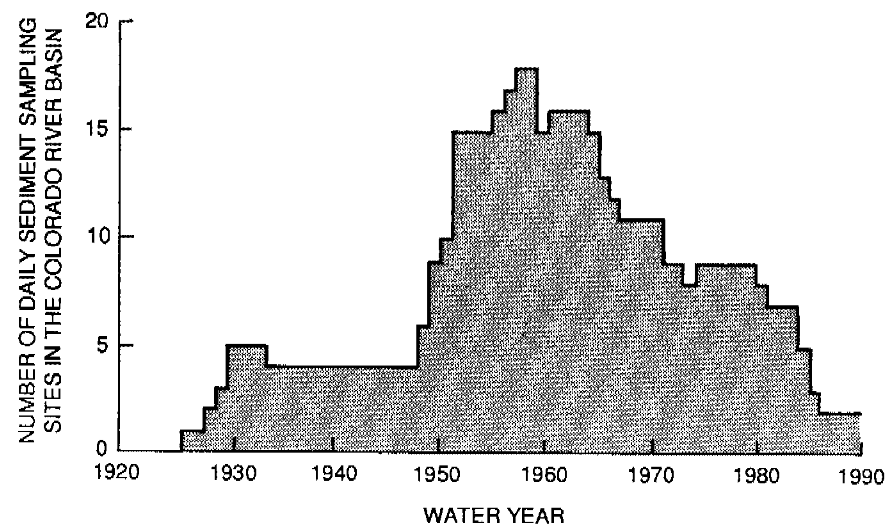

FIGURE 4-2 Number of active daily sediment sampling sites in the Colorado River basin with 10 or more years of record.

suspended sediment sampling stations was diminished. Gradually, one gaging station after another was eliminated. During the 1989 water year, suspended sediment was sampled daily at only two gaging stations in the upper Colorado River basin that had more than 10 years of record.

SOURCE AREAS OF RUNOFF AND SEDIMENT

Water and sediment are not contributed uniformly to the channel network of the Colorado River basin (Howard, 1947; Irons et al., 1965). Furthermore, the principal source areas of water and sediment differ greatly. Most of the annual water discharge comes from the headwater areas near the crest of the Rocky Mountains. Conversely, most of the sediment is contributed by the semiarid parts of the basin in southeastern Utah and adjacent States. The mean annual water discharge and sediment discharge measured during the period 1941-1957 at 11 gaging stations in the Colorado River basin upstream from Lake Mead are compared in Figure 4-1. After 1957, water and sediment discharges of the mainstem Colorado River and its principal tributaries were altered significantly as a result of construction of several reservoirs. The extent of water resource development prior to 1958, primarily irrigation and transmountain diversion, was modest, so that the values shown in Figure 4-2 are indicative of natural conditions.

Mean annual water discharge of the Colorado River near Grand Canyon from 1941 to 1957 was about 472 m^3/s, or 14.9 billion m^3/year, from a drainage area of 361,600 km^2. The combined mean annual discharge at the three farthest upstream gages shown in Figure 4-2 was 399 m^3/s, or 85% of the basin discharge at Grand Canyon. The contributing drainage area to the three upstream gages is 144,600 km^2, or 40% of the total drainage basin area. The estimated combined mean annual sediment discharge at these gaging stations was only 27 million tons/year or 31% of the total sediment discharge. Thus, the headwater tributaries contribute more than three fourths of the total water discharge but only about 31% of the sediment discharge of the Colorado River at Grand Canyon.

Most of the sediment discharged from the Colorado River basin is contributed by tributaries draining semiarid parts that include southeastern Utah, northeastern Arizona, and northwestern New Mexico. This area lies near the center of the Colorado Plateau. The largest of these tributaries, notably the San Rafael, Paria, Chaco, and Little Colorado rivers are shown in Figure 4-1. The portion of the Colorado River basin that lies upstream from Grand Canyon and downstream from Jensen, Utah, on the Green River, Cisco, Utah on the Colorado River, and Shiprock, New Mexico, on the San Juan River contributed about 59 million tons/year on an average, or about 69% of the basinwide sediment discharge, but supplied only 15% of the basinwide water discharge. The large sediment-contributing portion of the Colorado River basin upstream from Grand Canyon is 135,200 km^2, or ~37% of the total basin area. The most conspicuous sediment sources are areas of badland topography that developed on Mesozoic and Cenozoic mudstone and shale, principally the Wasatch, Mancos, Morrison, Chinle, and Moenkopi formations.

The characteristics of flow and sediment transport in those tributaries that supply most of the sediment to the Colorado River are not well known. Few gaging stations have been operated on these streams, and then only for a short time. The long-term contributions of water and sediment from many of these streams can be determined only by comparing the quantities measured at adjacent mainstem gaging stations. The only long records of water and sediment discharge for any of these tributaries have been collected on the Paria River to meet the requirements of the Colorado River Compact.

Mean monthly water and sediment discharges for the Colorado River before the construction of Glen Canyon Dam and discharges for the Paria River at Lee's Ferry are compared in Figure 4-3. Mean annual sediment discharge of the Paria River from 1947 to 1976 was 3.02 million tons/year or 4.6% of that transported by the Colorado River at Lee's Ferry. The mean annual water discharge, however, was only 0.72 m^3/s, or 0.16% that of the Colorado River at Lee's Ferry. Compared with the Colorado River basin, the Paria River basin yields three times as much sediment and one-tenth as much water per unit area.

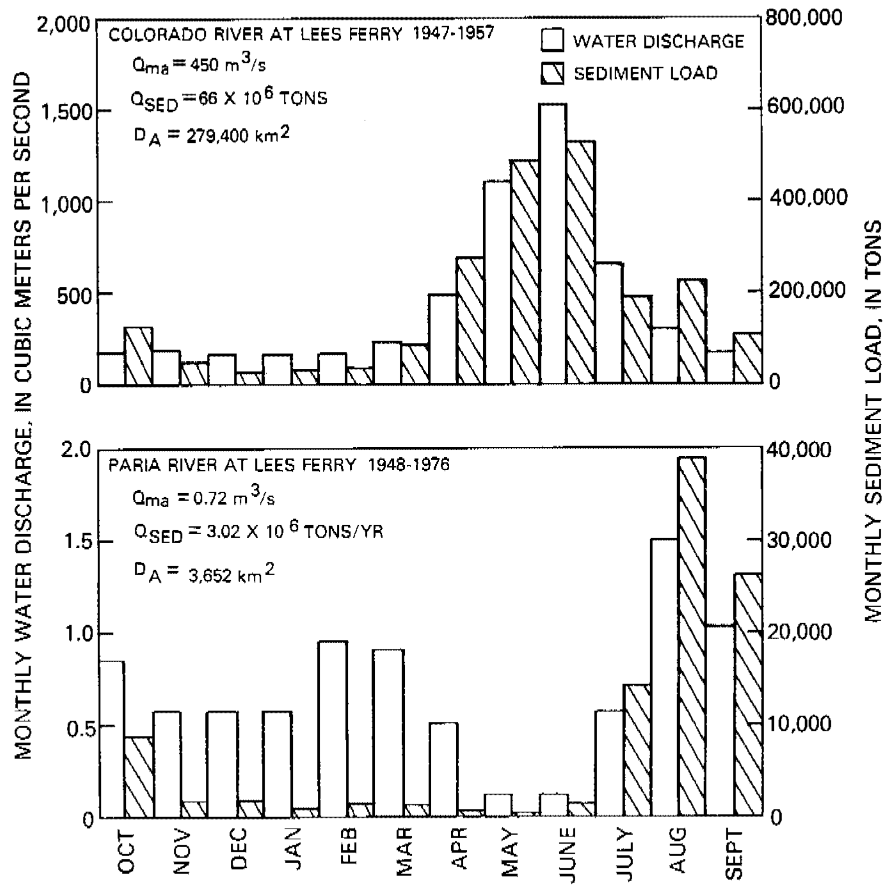

FIGURE 4-3 Mean monthly water and sediment discharges of the Colorado River and Paria River at Lee's Ferry, Arizona.

Maximum monthly water discharges occur in the Paria River during August and September (Figure 4-3). During the period of record from 1923 to 1986, two-thirds of the annual peak discharges occurred in the months of August, September, and October. These floods are a result of intense but short-duration thunderstorms that increase the discharge from a base flow of less than 1 m^3/s to several tens of cubic meters per second for a few days. The largest of these floods have transported most of the sediment outflow from the basin. Between 1947 and 1976, 50% of the sediment was transported on just 74 days, or just 0.7% of the time.

A comparison of the longest sediment records in the Colorado River basin upstream from Lake Mead indicates that the annual suspended sediment load for a given annual runoff was much greater before 1941 than after 1942. The relationship of annual runoff and suspended sediment loads recorded at the Colorado River near Grand Canyon between 1925 and 1957 is plotted in Figure 4-4. The mean annual suspended sediment load of the Colorado River near Grand Canyon was 195 million tons/year during the period 1925-1940 compared with 85.9 million tons/year during the period 1941-1957. A similarly dramatic decrease in the annual suspended sediment load for a given discharge occurred simultaneously at the Green River at Green River, Utah, Colorado River at Cisco. Utah, and the San Juan River near Bluff, Utah. Mean annual water discharges during the two periods 1925-1940 and 1941-1957 were approximately the same at all of these gaging stations. The large decrease in suspended sediment loads at about the same time that the new sampler was deployed is suspicious and disturbing. Smith et al. (1960) concluded, however, that the decrease was real. They based their findings on the following: (1) the shift to smaller suspended sediment load occurred from 1940 to 1942, whereas the new sampler was not in use until April 1944; (2) although the comparison of the two samplers was incomplete and the results were inconsistent, the difference between the samplers was not large enough to explain the decrease in annual sediment loads; and (3) the quantity of sediment deposited in Lake Mead during the period 1936-1948 was between 1,780 million and 1,840 million tons and agrees very well with the reported quantity of sediment transported past the Grand Canyon gage, 1,800 million tons.

The decrease in mean annual sediment loads in the Colorado River near Grand Canyon after 1941 is quite large, nearly 100 million tons/year, and raises some significant questions for those who are interested in the future of the Colorado River, in particular: What caused the annual sediment load to decrease so rapidly over a large area? What is the "normal" or long-term annual sediment load at a given site on the Colorado River? What was the source of the additional sediment, and will the sediment loads of the Colorado River increase to the pre-1941 level in the future? If so, when and under what conditions?

Beginning about 1880, channels of the Paria, Little Colorado, Chaco, and other tributaries of the Colorado were entrenched and large arroyos were formed (Cooke and Reeves, 1976; Graf, 1983). Vast quantities of alluvial sediment were eroded from the valley fills and transported to the Colorado River as arroyos enlarged. This widespread and dramatic geomorphic event has been studied for more than 90 years and continues to be a topic of interest. Webb (1985) compiled a list of 116 journal articles and books that described the chronology of arroyo development on the Colorado plateau and evaluated the importance of various causal agents.

Many investigators have concluded that large floods were the immediate cause of arroyos throughout the Colorado plateau (for examples, see Gre-

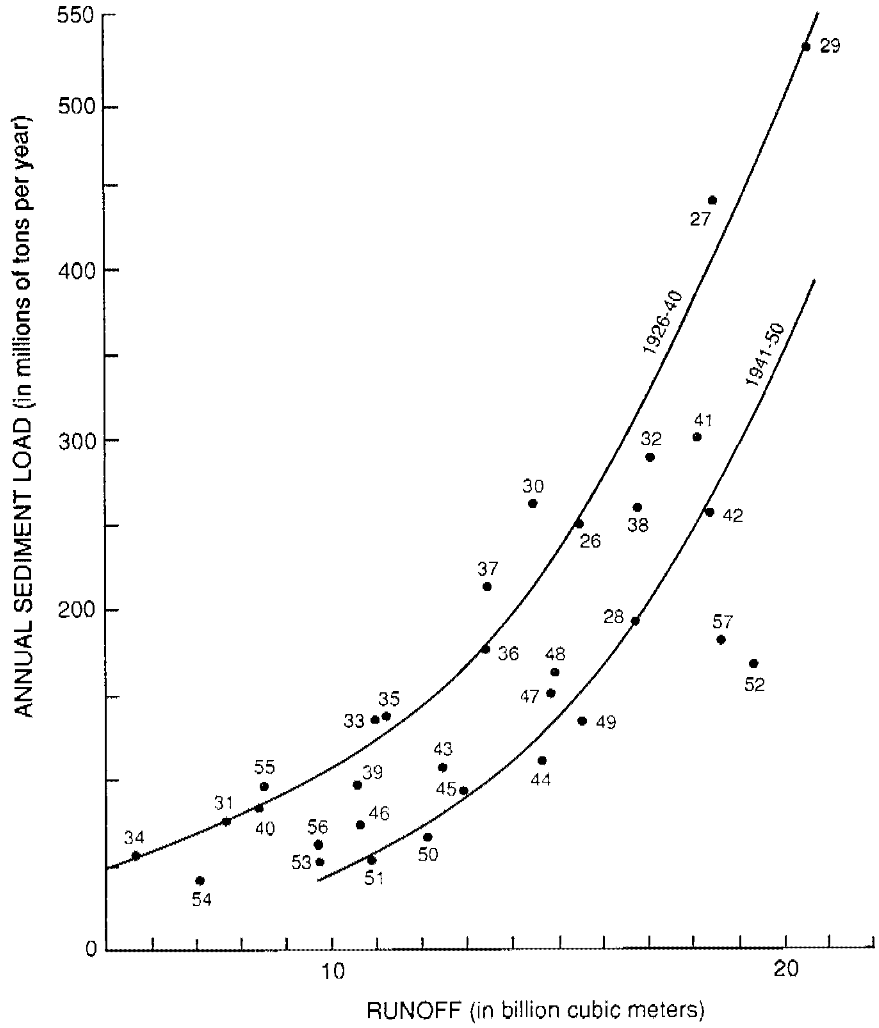

FIGURE 4-4 Relationship of annual runoff to annual sediment load in the Colorado River near Grand Canyon, 1926-1940 and 1941-1950. (Modified from an original by Smith et al., 1960.)
SOURCE: Smith et al., 1960.

gory and Moore, 1931; Thornthwaite et al., 1942; Graf, 1983; Webb, 1985; and Hereford, 1984, 1986). In the case of Kanab Creek and the Fremont River, historical accounts identify the dates of floods that initiated and enlarged the arroyos (Graf, 1983). For most streams, the period of arroyo formation is known only to within a few years. Although arroyos developed in all major tributaries draining the arid portion of the Colorado plateau during a 30-year span from 1880 to 1910, the period of intense arroyo formation varied from basin to basin. For example, entrenchment and arroyo development appear to have occurred somewhat later in the Escalante River, which drains the area immediately to the east of the Paria River. Using historical accounts and slackwater deposits, Webb (1985) determined that the Escalante River arroyo was initiated by a large summer flood that occurred on August 29, 1909. The arroyo was subsequently enlarged by recorded floods during 1910, 1911, 1914, 1916, and 1921.

A change in the frequency of large floods is indicated by the time series of annual peak flows recorded at the Paria River at the Lee's Ferry gage shown in Figure 4-5. Large floods occurred more commonly before 1942 than since 1942. Seven of the eight largest floods of the Paria River since 1924 occurred before 1942. The mean annual flood of the Paria River since 1942 is 106 m^3/s, or 55% of mean annual flood, 220 m^3/s, recorded prior to

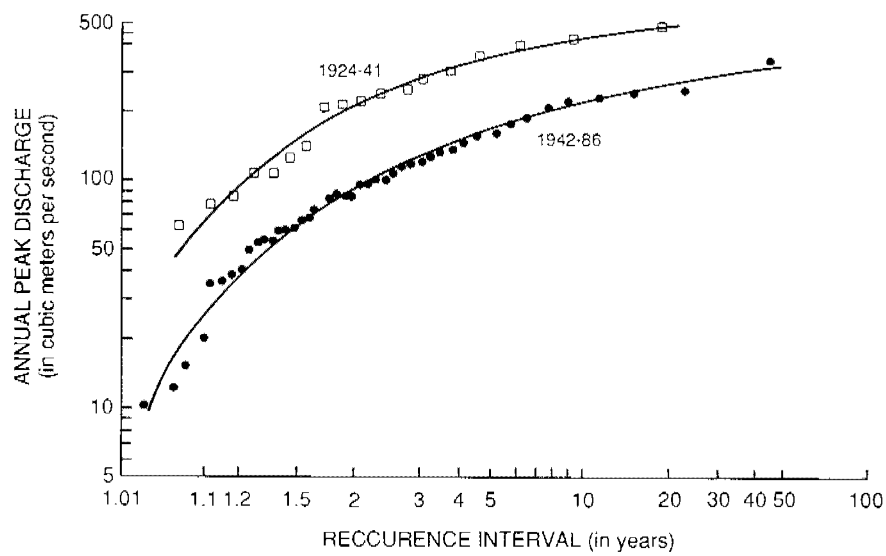

FIGURE 4-5 Comparison of recorded Paria River floods during the periods 1924-1941 and 1942-1986.

1942. Mean annual discharge of the Paria River at Lee's Ferry has decreased somewhat during the post-1942 period; however, the change is small compared with the decreased magnitude of annual peak flows. The mean annual discharge prior to 1942 was 1.03 m^3/s, compared with 0.77 m^3/s since 1942. The change is statistically significant at the 1% level. Hereford (1986) noted that the period of frequent larger floods corresponded to channel degradation and arroyo development. In contrast, the period of relatively small floods corresponded to channel aggradation and partial filling of arroyos.

Slackwater deposits along the Escalante River studied by Webb (1985) indicate that the frequency of Escalante River floods has varied during the past 2,000 years. Large floods occur most frequently between 1,200 and 900 years Before Present, 600 and 400 years Before Present, and in the past 100 years. The earlier periods of frequent floods appear to be correlative with previous Escalante River arroyos.

The sequence of channel changes in the Paria River basin as reconstructed by Hereford (1986), using stratigraphic, botanical, and photographic evidence, indicates that the channel degrades during periods of frequent large floods and aggrades during periods of small to moderate floods. An arroyo began to form in the Paria River channel in 1883 and attained its maximum size by 1890 (Gregory and Moore, 1931). The arroyo remained deep and wide until the early 1940s when channels throughout the basin began to aggrade. Within a decade of 1940, the Paria River channel narrowed appreciable and a vegetated floodplain developed. A comparison of the stage-discharge relationship determined at the Paria River at the Lee's Ferry gage before 1939 and after 1964 indicates that the channel had aggraded by as much as 2 m in storage. Since 1980, the Paria River channel has begun to degrade and widen (Hereford, 1986).

EFFECTS OF RESERVOIR STORAGE ON SEDIMENT BALANCE IN SELECTED REACHES OF THE COLORADO RIVER

As described above, the contribution of runoff and sediment per unit area varies greatly within the Colorado River. A majority of the annual runoff is contributed by the relatively high elevation (>3,000 m) parts of the basin along the Continental Divide, whereas most of the sediment is contributed by the semiarid parts of the basin near the center of the Colorado plateau. The downstream effects of a reservoir depend not only on the size and operating schedule of a reservoir but also on the location of the reservoir within the basin relative to the major runoff and sediment-contributing areas. An identical reservoir located at different sites in the Colorado River basin would have very different downstream effects on sediment transport and deposition.

GREEN RIVER DOWNSTREAM FROM FLAMING GORGE RESERVOIR

Andrews (1986) described the downstream effects of Flaming Gorge Reservoir on streamflow and sediment transport in the Green River. Prior to the construction of a dam in Flaming Gorge, a quasi-equilibrium condition appears to have existed downstream in the Green River channel; that is, over a period of years, the transport of sediment out of a given river reach equaled the supply of sediment into the reach. Since regulation by Flaming Gorge Reservoir began in 1962, the mean annual sediment discharge at downstream gages has decreased substantially. The mean annual sediment discharge has decreased by 54% (from 6.29 million to 2.92 million tons) at the Jensen gage, by 48% (from 11.6 million to 6.02 million tons) at the Ouray gage, and by 48% (from 15.5 million to 8.03 million tons) at the Green River, Utah, gage. The decrease in mean annual sediment discharge at the Ouray and Green River, Utah, gages far exceeds the quantity of sediment trapped in the reservoir.

Post-reservoir annual sediment budgets show that a majority of the Green River channel is no longer in quasi equilibrium. Three distinct longitudinal zones involving channel degradation, quasi equilibrium, and aggradation were identified. Beginning immediately downstream from the dam and extending downstream 110 river km, sediment transport out of the reach exceeds the tributary contribution, and the channel is degrading. The length of the degrading reach, however, is relatively limited because of the large quantity of sediment supplied by tributaries.

In the reach between river km 110 and 269 downstream from Flaming Gorge Reservoir, the quantity of sediment supplied to the reach from upstream plus tributaries approximately equals the transport of sediment out of the reach over a period of years. This reach appears to be in quasi equilibrium, as there is no net accumulation or depletion of bed material. Downstream from river km 269 to the mouth (river km 667), the supply of sediment from upstream and tributary inflow exceeds the transport of sediment out of the reach by 4.9 million tons/year on an average.

The decrease in mean annual sediment transport at the Jensen and Green River, Utah, gages since 1962 is due entirely to a decrease in the magnitude of river flows that are equaled or exceeded <30% of the time. The quantity of sediment in transport at a given discharge downstream from Jensen, Utah has not decreased in the post-reservoir period. Daily mean water discharges with a duration of 5% or less have decreased in magnitude by 25% during the post-reservoir period at both the Jensen and Green River, Utah, gages. The magnitude of daily mean discharges with a duration >30%, however, has increased to the extent that the mean annual runoff measured during the pre- and post-reservoir periods is virtually unchanged at both gages. The decrease in annual sediment transport thus results from a more uniform annual hydrograph rather than from a decrease in the annual runoff.

Ferrari (1988) described a detailed survey of sediment deposition in Lake Powell for the period March 1963 to September 1986 and concluded that 1.07 billion m^3 of sediment had been deposited in the reservoir. Assuming a unit mass of 1.04 tons/m^3 as determined by Smith et al. (1960) for Lake Mead, 1.11 billion tons of sediment accumulated in Lake Powell over the 24-year period. As described above, the mean annual sediment load of the Colorado River at Lee's Ferry during the period 1941-1957 was 66.1 million tons/year. This gaging station is located only 23 km downstream from Glen Canyon Dam, and there are no significant tributaries to the intervening reach. Thus, the quantity of 66 million tons/year is probably a reasonable estimate of the amount of material that would have been deposited in Lake Powell from 1963 to 1986 if there had been no additional development of water resources in the upper Colorado River basin after 1957. The actual mean annual accumulation of sediment in Lake Powell is about 44.4 million tons/year or 19.7 million tons/year less than the 1941-1957 average. The mean annual quantity of sediment deposited in major reservoirs upstream from Lake Powell is approximately 4 million tons/year. The remaining quantity of sediment, approximately 15.7 million tons/year, is sediment supplied to the principal upper basin tributaries, the Green, San Juan, and mainstem Colorado, but is not being transported downstream because regulation has greatly diminished peak discharges.

COLORADO RIVER DOWNSTREAM FROM GLEN CANYON DAM

Presently, the effect of various discharges in the Colorado River downstream from Glen Canyon Dam upon the riverine environment of Grand Canyon National Park is being studied in great detail. The contribution of sediment to the Colorado River through Grand Canyon is especially important, as it will influence significantly the distribution and size of sandbars (commonly called beaches) along the Colorado River. These sandbars are deposited during periods of relatively large discharge and become exposed when the stage falls. The bars are composed of sand with a median diameter of about 0.20 mm, with less than a few percent coarser than 0.50 mm, Schimdt and Graf (1990). Sediment particles of this size are transported primarily suspended within the main core of flow at commonly occurring flows. These particles, however, settle out and accumulate in areas of relatively low turbulence along the channel margin.

The National Park Service is concerned with the decreases in size and number of sandbars since the closure of Glen Canyon Dam in 1962. They have identified the preservation of sandbars as one of their highest-priority objectives. Sandbars are used by river runners as camp sites. They are also important features of the riparian and aquatic ecosystem. Fundamentally, the maintenance of sandbars along the channel margin of the Colorado River through Grand Canyon depends on determining the discharge and its duration which will build sandbars without causing a net depletion of the sand-size material in the Grand Canyon reach. Our understanding of current sediment inflow and outflow from the Grand Canyon will be described below.

The downstream effects of Glen Canyon Dam on the Colorado River differ somewhat from those of Flaming Gorge Dam. Glen Canyon Dam is located downstream from significant sediment-contributing areas, and therefore a relatively large quantity of sediment is deposited in Lake Powell. The quantity of sand-size sediment stored in the channel bed, banks, and floodplain of the Green River downstream from Flaming Gorge Reservoir is very much greater than the quantity of sand-size sediment stored in the Grand Canyon in both absolute and relative terms compared with the historical mean annual loads. The relative large discharges that have historically transported most of the sediment through Grand Canyon, however, have also been greatly reduced. The Paria and Little Colorado rivers join the Colorado River downstream from Glen Canyon Dam and contribute a large quantity of sediment (Figure 4-1). During the post-1941 period, these two tributaries supplied approximately 12.3 million tons of sediment per year to the Colorado River.

A comparison of mean annual sediment load during the period 1941-1957 indicates that the sediment load at the Colorado River near the Grand Canyon exceeded the sediment load at the Colorado River at the Lee's Ferry by about 20 million tons/year, see Figure 4-1. The difference between the quantity of sediment supplied by the Paria and Little Colorado Rivers, which represent 93% of the intervening drainage area, and the increase between the Lee's Ferry and Grand Canyon gages can be explained by (1) a few percent error in either the Grand Canyon or Lee's Ferry sediment sampling records and (2) net erosion of the reach between Lee's Ferry and Grand Canyon that occurred during the period 1941-1957.

It is reasonable to expect that the quantity of sand stored within and adjacent to the channel of the Colorado River through Grand Canyon increased between 1880 and 1941, during the period of relatively large sediment load, and that the quantity of sand stored in the channel has decreased since 1941. At present, there is no direct evidence for or against this hypothesis except the analysis of D. Burkham (personal communication) showing a 1.6-m decrease in the low-flow streambed elevation at the Lee's Ferry gage from 1941 to 1957.

The mean annual sediment load of the Colorado River near Grand Canyon under the present conditions cannot be stated with great certainty because daily sampling of sediment concentration at this gage was discontinued in 1972. An estimate of the mean annual sediment load may be computed from the recorded daily discharges, and a relationship may be derived from the correlation of occasional samples of sediment concentration and the instantaneous discharge. Using this approach, the estimated mean annual sediment load of the Colorado River near Grand Canyon is approximately 11 million tons/year under present conditions, compared with 85 million tons/year during the period 1941-1957, immediately prior to the construction of Glen Canyon Dam. In contrast to the situation on the Green River downstream from Flaming Gorge Reservoir described above, the decrease in mean annual sediment load in the Colorado River near Grand Canyon is not solely due to a decrease in relatively large discharges. The concentration of sediment suspended in the flow at the Grand Canyon gage for a given discharge has decreased by a factor of 2-3. This decrease is undoubtedly due to a net depletion of sand-size sediment stored within the active channel, $\leq$1,400 m^3/s, since the closure of Glen Canyon Dam in 1962.

A comparison of sediment supply from tributaries and the transport of sediment downstream indicates that the Colorado River through Grand Canyon is approximately in equilibrium under the current operating schedule at Glen Canyon Dam. That is, the inflow of sediment appears to approximately equal the outflow of sediment over a period of years. The quantity of sediment stored in the reach between the Lee's Ferry and Grand Canyon gaging stations is estimated to be approximately 40 million tons (T. J. Randle and E. L. Pemberton, written communication), or less than four times the mean annual flux of sediment. Thus, even a relatively small, but persistent imbalance between the inflow and outflow of sediment to this reach over a period of years will cause appreciable changes in the quantity of sediment stored within the reach.

A long-term equilibrium between sediment inflow and outflow from the Grand Canyon reach, however, will not be sufficient to ensure the presence of large, exposed sandbars along the channel margin at commonly occurring flows. These bars are built and maintained by sustained periods of flow sufficient to inundate the bar crest by a few feet. Without sustained periods of high flow, the existing sand bar will be degraded through erosion of material and the encroachment of vegetation.

Periods of sustained, high flow followed by a corresponding decrease in flow throughout the remainder of the year will increase the mean annual sediment load of the Colorado River through Grand Canyon. The comparison of sediment inflow and outflow from the Grand Canyon reach described above suggests that the downstream transport is currently about equal to the tributary contribution. The challenge is to select the range of flows that will maximize the accumulation of sand on bars without exceeding the long-term rate of sediment supply. Our ability to define the optimum range of Colorado River flow through Grand Canyon depends on knowing in great detail (1) the long-term rate of sediment supply by tributaries to the mainstem Colorado River, (2) the longitudinal variation in the quantity of sediment transported at a given discharge, and (3) the dynamics of flow and sediment transported in areas of lateral flow separation (eddies), which control the deposition and erosion of sand bar deposits. At this time, we do not understand any of these topics well enough to determine precisely the range of streamflow that will maintain and, we hope, enhance occurrence of sandbars through the Grand Canyon reach.

CONCLUSIONS

Long-term daily sampling of suspended sediment transport began in the Colorado River basin at the Grand Canyon gage in 1925. Over the next three decades, the network of sediment sampling sites was expanded greatly. In 1957, there were 18 gaging stations where suspended sediment concentration had been sampled daily for 10 or more years. The network of sediment sampling sites in the Colorado River is probably the most extensive and detailed ever operated.

The primary objective of this sediment sampling network was to provide information for the planning and design of reservoirs in the Colorado River basin. Most of these reservoirs were completed during the early 1960s, and nearly all of the sediment sampling sites have been discontinued. During the 1989 water year, sediment concentration was sampled daily at only two gaging stations in the upper Colorado River basin. In recent years, public interest in and concern for the aquatic and riparian resources of the Colorado River basin have increased greatly. Comprehensive management of these resources will require rather detailed knowledge of sediment supply, transport, and deposition. Extensive analysis of the available sediment transport information using sophisticated water and sediment routing models together with reestablishment of selected long-term sediment sampling sites in the Colorado River basin will be necessary to achieve this goal.

Water and sediment are not contributed uniformly to the channel network of the Colorado River basin. Furthermore, the principal source areas of water and sediment differ greatly. Most of the annual water discharge comes from the headwater areas near the crest of the Rocky Mountains. Conversely, most of the sediment is contributed by the semiarid parts of the basin near the center of the Colorado plateau. There is also an important difference in the season of flooding between the principal source areas of water and sediment. In the high-elevation parts of the basin, major tributaries, and the mainstem Colorado, the flood season occurs in the spring, associated with snowmelt. Conversely, the tributaries draining the high-sediment-contributing parts of the basin flood most often during late summer and early fall as a result of thunderstorms. Throughout the Colorado River basin, floods transport a majority of the annual sediment load. Thus, a majority of the sediment load of the Colorado River is contributed to the channel by tributaries during July, August, and September; however, it is transported in the mainstem during April through June. The largest concentrations of suspended sediment in the Colorado River and its major tributaries occur during the season of maximum sediment supply rather than maximum sediment transport.

The respective flood seasons of the principal water and sediment source area are associated with different atmosphere circulation patterns. Furthermore, long-term changes and shifts in the relative strength of either pattern appear to be largely independent of the other pattern. Therefore, periods of relatively large sediment supply to the Colorado River and its major tributaries do not necessarily correspond to periods of relatively large flood flows in the Colorado River and its major tributaries.

During the period from 1880 to 1941, floods were larger and more frequent than in the period since 1941. Vast quantities of sediment were eroded by those floods, and large arroyos were formed in all of the tributaries draining the Colorado plateau. Suspended sediment concentrations at a given discharge as well as the annual sediment loads of the Colorado River and its major tributaries were substantially larger before than after 1941. The relatively large suspended sediment concentrations were probably associated with an increase in the quantity of sand-size material stored within the channel. Enlargement of these arroyos has been reversed since 1941, and significant quantities of material have been deposited in the arroyo channels over the past 50 years. The water and sediment discharges of tributaries to the Colorado River draining the Colorado plateau region have been sensitive to changes in climate over the past century. Further study of the relationship between the hydrology of these streams and variations in the regional climate should be undertaken.

The Colorado River is one of the most highly regulated rivers in the world. Total reservoir storage capacity is approximately four times the mean annual runoff. With the exception of relatively small tributaries, flow and sediment transport in the channels of the Colorado River basin have been extensively altered by the construction and operation of reservoirs. The downstream effects of a reservoir depend not only on the size and operating schedule of the reservoir but also on the location of the reservoir within the basin relative to the major runoff and sediment-contributing areas. Identical reservoirs located at different sites in the Colorado River basin would have very different effects on the channel downstream.

Alteration of flow and sediment transport downstream from reservoirs in the Colorado River basin changes the sediment inflow and outflow to river reaches in a complex longitudinal pattern. Downstream from Flaming Gorge

Reservoir on the Green River, the annual load of sediment transported in the channel immediately downstream from the dam exceeds the supply over a period of years, and the channel is degrading. Between river km 110 and 269 downstream from the dam, the annual load of sediment transported in the channel is approximately equal to the quantity of sediment contributed by tributaries, and the channel is in a quasi-equilibrium condition. Downstream from river km 269, the quantity of sediment contributed by tributaries exceeds the annual sediment load transported in the channel, and the channel is aggrading. The longitudinal sequence is an inevitable result of a significant reduction in flood flows and a relatively large sediment contribution by tributaries to the mainstem channel.

Post-reservoir changes in flow and sediment transport in the Colorado River through Grand Canyon are similar to those that have occurred in the Green River immediately downstream of Flaming Gorge Dam. Annual flood flows have been greatly reduced in magnitude, and the quantity of sand stored within the active channel has been substantially depleted. Two tributaries supply relatively large quantities of water but little flow compared with the Colorado River. The concentration of suspended sediment at the Colorado River near Grand Canyon at a specific discharge has decreased by a factor of 2.3 for commonly occurring flow. Since 1970, the mean annual sediment load of the Colorado River near Grand Canyon has been approximately 11 million tons, which is about the estimated contribution of sediment to the reach between Lee's Ferry and Grand Canyon. Therefore, it appears that currently the supply of sediment to the reach approximately equals the quantity of sediment transported out of the reach.

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